Method for Smoothing and Polishing Surfaces by Treating Them
With Energetic Radiation

**Technical Field**

The present invention relates to a method for smoothing and
polishing surfaces by treating them with energetic radiation,
in particular laser radiation, in which the to-be-smoothed
surface is remelted at least once in a first treatment step,
using the energetic radiation and first treatment parameters
down to a first remelting depth which is greater than a
structural depth of the to-be-smoothed structures of the to-
be-smoothed surface and is ≤ 100 µm. The method can be used,
for example, in mechanical engineering for finishing tools and
molds. In modern mechanical engineering and, especially, in
tool and mold construction, there are high demands on the
quality of technical surfaces. However, in manufacturing
processes, such as for example milling or eroding, the
achievable surface roughness is limited. If smooth, glossy,
respectively polished surfaces, are required, additional
manufacturing processes, such as abrading and polishing, must
follow.

**Prior Art**

Nowadays, tool and mold finishing occurs predominantly by
means of manual polishing. Electrically or pneumatically
driven devices with up to ultrasonic operating frequencies
support the manual work. Until the final polishing step, the
steps rough abrasion, fine abrasion and polishing with
increasingly finer polishing pastes up to diamond paste must
be carried out. Usual polishing times are about 30 min/cm2.
Peak-to-valley heights of Ra < 0.01 µm  are achievable.

Mechanical polishing methods have the drawback that prior art
methods cannot be applied or only yield unsatisfactory results

if the to-be-polished surfaces have complex three-dimensional geometries.

DE 42 41 527 discloses a method of hardening machine components by heating the surfaces of the component using a laser beam, with which the surface of the machine component can simultaneously be smoothed. In this case, the components are chilled cast parts with a ledeburitic structure or steel parts with a pearlitic structure. In this method, a surface layer of the component is heated using a laser beam until close to the melting point in such a manner that in a boundary layer, diffusion of the carbon occurs out of the cementite lamella of the ledeburite, respectively out of the pearlite, into the soft intermediate ferrite lamella regions. The diffusion of the carbon results in the desired hardening of the surface. Setting the laser parameters with energy densities in the range of $10^3 - 10^5$ W/cm$^2$ results, moreover, in marked evaporation and melting of a thin surface skin, which simultaneously leads to micro-smoothing of the surface. This application requires the laser power of approximately 4 - 12 kW.

Furthermore, EP 0 819 036 B1 describes a method using a laser to polish with any three-dimensional mold surface in which the contour of the to-be-treated workpiece is first measured and then the treatment strategy and the treatment parameters are derived from the prescribed desired shape and the current shape. Smoothing and polishing are realized by a removal process. For laser polishing, a region of low laser intensity is proposed as greater material removal is not desired in this application. However, there is no other mention in this printed publication of treatment strategies or treatment parameters for achieving an optimum degree of smoothing. The heart of the proposed method is recognizing any deviation of the current shape from the desired shape by scanning using a three-dimensional contour measuring device. From this deviation, the suited treatment parameters are calculated and utilized. These steps are repeated until the desired shape is obtained. However, the required use of a three-dimensional

contour measuring device is complicated and, due to the
precision demanded, connected with very high costs.

DE 197 06 833 A1 discloses a method for smoothing and
polishing surfaces according to the generic part of claim 1.
In this method, the surface is brought to start to briefly
melt with pulsed laser radiation having a pulse duration of
between 10 ns and 10 μs to a depth of 2 to 3 μm with each laser
pulse. The new molten mass generated with each laser pulse
solidifies again before the next laser pulse occurs. However,
the method is only suited for smoothing surfaces with a
minimal surface roughness of Rz ≤ 3 μm.

The object of the present invention is to provide a method for
smoothing and polishing surfaces by treating them with
energetic radiation, in particular laser radiation, and this
method does not require expensive measuring instruments and
can be used to automatically polish any three-dimensional
surface, in particular metal surfaces, quickly and
inexpensively.

**Description of the Invention**
The object on which the present invention is based is solved
using the method according to claim 1. Advantageous
embodiments of the methods are the subject matter of the
subordinate claims or can be drawn from the following
description and the preferred embodiments.

In the present method for smoothing, respectively polishing,
surfaces by treating them with energetic radiation, for
example laser radiation or electron radiation, the to-be-
smoothed surface is remelted in a first treatment step using
the energetic radiation and employing the first treatment
parameters at least once down to a first remelting depth of
approximately 5 to 100 μm, which is greater than a structural
depth of the to-be-smoothed structure of the to-be-smoothed
surface, using continuous radiation or pulsed radiation with a
pulse duration of ≥ 100 μs.

Preferably a second treatment step is conducted then utilizing energetic radiation with second treatment parameters. In this second treatment step, the micro-roughness remaining after the first treatment step is leveled by remelting down to a second remelting depth, which is less deep than the first remelting depth, and by evaporating roughness peaks. This preferred embodiment of the present method is thus based on a multi-step treatment process, which can be divided into rough treatment and fine treatment. In the first treatment step, also referred to in the following as rough treatment, the to-be-smoothed surface is remelted once or multiple times down to a first remelting depth in a boundary layer using the energetic radiation and employing the first treatment parameters. In this remelting process, the macro-roughness which, for example may stem from previous milling, respectively eroding process, is removed. In a second treatment step, also referred to in the following as fine treatment, the remaining micro-roughness on the surface is then leveled using energetic radiation and employing the second treatment parameters. The second treatment step of the fine treatment comprises therefore a combination material removal and remelting process in which the thickness of the remelted boundary layer is less than the thickness of the remelted boundary layer of the first treatment step.

With the proposed method, any three-dimensional workpiece surface can be quickly and inexpensively automatically polished. Measuring the contour of the to-be-polished surface is not required. Moreover, due to the multi-step treatment process with different first and second treatment parameters, a high glossiness of the polished surface is achieved.

The method is particularly suited for smoothing three-dimensional metal surfaces. For example, it has already been used to smooth and polish workpieces made of the steels 1.2343, 1.2767 and 1.2311 as well as of titanium materials. Of course, the present method can also be utilized with other metals and non-metals such as, for example, workpieces made of plastic. Someone skilled in the art needs only to adapt the

treatment parameters to the to-be-treated materials in order
to obtain the conditions for the first treatment step and, if
need be, for the second treatment step. The first treatment
parameters are preferably selected in such a manner that no
ablation of material or only a smallest possible ablation of
material occurs, since smoothing is effected in this first
treatment solely by remelting of the boundary layer down to
the first remelting depth. In smoothing and polishing
plastics, conducting just the first step suffices to obtain
excellent smoothing results.

By utilizing continuous or pulsed energetic radiation, in
particular laser radiation, with a great pulse duration of $\geq$
100 μs single or multiple remelting of the boundary layer down
to the first remelting is achieved. In contrast to this, in
the second treatment step, pulsed radiation with a pulse
duration of $\leq$ 5 μs is preferably employed to generate the high
intensities required for the combination remelting and
material removal process. In this second treatment step, the
surface is preferably only remelted down to a second remelting
depth of maximally 5 μm, whereas the greater first remelting
depth of the first treatment step preferably lies between 10
and 80 μm. This first remelting depth of the first treatment
step is dependent on the size of the macro-roughness of the
to-be-smoothed workpiece. The greater the to-be-smoothed
macro-roughness, the greater the depth of the first remelting
depth has be selected in order to achieve sufficient leveling
of the macro-roughness.

Furthermore, smoothing and polishing of the surface with
energetic radiation should be conducted under a protective gas
shroud. This may occur by treatment within a process chamber
filled with protective gas or by feeding the protective gas to
the surface areas being treated by means of a jet. Argon,
helium or nitrogen can, for example, be used as the protective
gas.

Optimum smoothing results are yielded with the present method,
if the surface of the workpiece is remelted multiple times in

succession in the first treatment step, preferably with a first remelting depth that decreases from remelting process to remelting process. The treatment with energetic radiation is, as in the second treatment step, conducted in a prior art manner by scanning the surface with the energetic beam. This scanning occurs in parallel paths, with the individual paths defined by the width of the single energetic beams partially overlapping. In the multiple remelting of the surface, the treatment direction is preferably turned by an angle of, for example, 90° between the single remelting processes in such a manner that the paths of successive remelting processes lie perpendicular to each other.

**Brief Description of the Drawings**
The present method is made more apparent in the following using a preferred embodiment with reference to the accompanying drawings without the intention of limiting the scope or spirit of the inventive idea.

Fig. 1       shows a schematic sketch of the scanning of
             the to-be-smoothed surface using a laser beam;

Fig. 2       shows a rather schematic representation of an
             example of an original profile of a surface
             including the results of various polishing
             concepts;

Fig. 3       shows a comparison of surface profiles of an
             unprocessed milled surface with a surface profile
             of the surface of following the first treatment
             step of the present method;

Fig. 4       shows an example of the treatment strategy for
             successive processing a multiplicity of adjacent
             treatment sections;

Fig. 5       shows an example of the treatment strategy for

retaining edges on the to-be-smoothed surface;

Fig. 6       shows a schematic representation of an example of
             the different remelting depths of the first and
             second treatment steps of the present method;

Fig. 7       shows a representation comparing the measured
             surface profile following the first and following
             the second treatment step;

Fig. 8       shows a photographic representation of a surface
             before smoothing using the present method following
             the first treatment step and following the second
             treatment step; and

Fig. 9       shows an example of smoothing a surface using the
             present method while retaining structures of
             significance.

**Ways to Carrying Out the Invention**
Figure 1 shows very schematically the treatment process in the
present method by scanning the surface 1 of the to-be-treated
workpiece 2 with a laser beam 3. The laser beam 3 is led in
parallel paths 6, preferably meandering, over a section 4 of
the to-be-treated surface 1. The width 5 (track width) of the
individual paths 6 is given by the diameter 7 of the laser
beam on the surface 1. In order to obtain a suited intensity
or track width, this beam diameter 7 may, of course, be
adapted with the aid of a interconnected optic. The laser beam
3 is led over the surface 1 in the direction indicated by the
arrow with a given scanning velocity. Adjacent paths 6 overlap
by selecting a track offset 8 which is smaller than the track
width 7. The length 9 of the individual paths 6 can be
predefined. It is, however, limited by the laser scanning
system employed. Therefore, in order to treat large surface
areas, a multiplicity of shown sections 4 have to be treated
successively. Figure 1 also, indicates, by way of example a
first remelting depth 10 down to which the workpiece 2 is

remelted in the first treatment step of the present method. In addition to a round beam cross section, another beam cross section 7a, for example rectangular respectively linear can, of course, also be employed as is indicated by way of example in the lower part of figure 1.

In this first treatment step, a continuous or pulsed laser system with pulse lengths of > 0.1 ms is utilized. The boundary layer of the workpiece 2 is melted just so deep that the roughness present on surface 1 is smoothed. This first remelting depth 10 is adapted to the original roughness. Typical first remelting depths 10 lie in the range between 10 and 100 μm. The greater the unevenness of the original surface 1, the deeper the remelting has to be in order to permit the necessary volume compensation. For example, greater first remelting depths are required for milled surfaces than for abraded surfaces. Using a continuous laser beam, respectively a pulsed laser beam with long pulse lengths, prevents evaporation of material from the surface 1 in this rough treatment of the first treatment step, permitting thereby carrying out the polishing process with substantially less energy than is the case with applications in which the macro-roughness is removed. Furthermore, local overheating in the molten bath which leads to material removal and to undesired molten bath movements and thus to deteriorating the surface roughness is largely prevented.

For this first treatment step of the present method, the beam source is preferably a Nd:YAG laser, a $CO_2$ laser, a diode laser or an electron beam source. The laser power lies in the range from 40 - 4000 W. The beam diameter being 100 - 1000 μm, the scanning velocity is approximately 30 - 300 mm/s and the track offset is selected between 10 to 400 μm. The interaction times with the surface lie preferably between 200 μs and 10 ms. Passing surface 1, respectively the section 4 just undergoing treatment, multiple times and turning the treatment direction by, for example, 90° permits improving the first treatment step further.

Figure 2 shows, as an example, in a very schematic representation a section of an abstracted original profile (figure 2a) of a to-be-treated surface with macro-roughness with a height 11 of 10 μm and a width of, respectively a distance 12 of 300 μm (not shown to scale). These measures correspond to typical original dimensions of the original roughness of a surface with a milling structure.

Figure 2c shows the effect of the first treatment step of the present method in which the surface (previously: broken line; after: continuous line) is remelted to a remelting depth of approximately 10 μm. Remelting the material in this remelting step levels the macro-roughness.

In comparison, figure 2b shows a result as obtained by flat removal of surface material in polishing. This example clearly shows that the macro-roughness cannot be completely removed by flat removal (20: areas of removed material).

Figure 3 finally shows measured surface profiles of a to-be-treated, respectively treated, surface. Figure 3a shows a measured profile of an untreated, milled surface where the macro-roughness is clearly visible. Following carrying out the first treatment step of the present method, a profile of this surface is obtained, as depicted in figure 3b. This figure clearly shows definite smoothing of the macro-roughness after the first treatment step.

In the case of large to-be-smoothed surfaces, a multiplicity of sections 4 of surface 1 depicted in figure 1 have to be treated successively with laser radiation. In order that the boundaries, respectively the beginning of the respective adjacent section (4) are not visible on the finished workpiece, the treatment parameters are continuously changed, respectively changed in steps, down to the border of these sections 4 in such a manner that the first remelting depth is reduced. Figure 4 shows in a section an example of such a type of treatment strategy. In this section, two treated sections 4 are adjacent to each other. In the transition region between

the two sections 4, the remelting depth 10 is continuously reduced in such a manner that there are no abrupt changes in smoothing in this transition region. Changing the treatment parameters down to the border of section 4 can be achieved by defocusing the laser beam, by reducing the power, for example using power ramps, by increasing the feed rate, for example using feed rate ramps, or by varying the position of the beginning, end, or turning points.

In polishing injection mold tools, it is essential that the edge at the separation plane of the tool is not rounded, because this would lead to undesired formation of crests on the plastic parts produced with the tool. In order to prevent rounding at the to-be-retained edges of the surface of the tool, a similar strategy can be used in carrying out the present method as in successively processing adjacent treatment sections. The treatment parameters are changed toward the edge in such a manner that the first remelting depth decreases. The edge itself must not be remelted as this would always lead to rounding it. Figure 5 shows that of the two sections of surface 1 adjacent at edge 13, the first remelting depth 10 decreases toward edge 13 so that no remelting occurs at the edge 13 itself. This reduction of the remelting depth can be achieved by decreasing the laser power, respectively increasing the feed rate toward the edge 13.

After smoothing the surface in the first treatment step, the degree of gloss is raised in a second treatment step using a pulsed laser with pulse lengths of < 1 μs. By selecting a second remelting depth 14, which is less than the first remelting depth 10, a very thin boundary layer of < 5 μm is remelted and the remaining micro-roughness peaks 15 are removed by evaporating the material. This is depicted very schematically in Figure 6 showing the first remelting depth 10 and the second remelting depth 14 as well as the remaining micro-roughness peaks 15 remaining after the first treatment step. A glossy surface is obtained with this second treatment step.

Figure 7 shows a measured profile of a surface smoothed using the present method. Depicted in the left part of the figure is the surface roughness remaining after the first treatment step, and depicted in the right part of the figure is the surface profile after the second treatment step. In this representation, the reduction in the thickness of the line indicates the substantial reduction of the micro-roughness to a magnitude of ≤ 0.1 μm remaining after the first treatment step.

Treatment in the second treatment step also occurs by scanning the surface, for example on a meandering path. Typical treatment parameters for the second treatment step are the use of a Nd:YAG laser or an excimer laser with a laser power of 5 - 200 W and a scanning velocity of 300 - 3000 mm/s with a beam diameter of 50 - 500 μm and a track offset of 10 - 200 μm.

Finally, figure 8 is a photograph of a surface showing a region 16 following milling, a region 17 following the first treatment step and a region 18 following the second treatment step. The glossy surface yielded by the second treatment step is quite evident in this figure compared to the smoothing of the first step, respectively compared to the unsmoothed surface.

With suited selection of the treatment parameters, surfaces can also be polished in such a manner that the structures of significance present in a surface are retained, undesired micro-roughness, however, is removed. By selecting the treatment parameters, in particular the first remelting depth, it can be set which structure of the surface are smoothed and which are to remain. Thus, for example, an eroded surface can be polished to a high gloss while retaining the erosion structure and in this way producing grained surfaces for injection mold tools, as is shown, for example, in figure 9. The upper section of the figure shows an eroded, unpolished surface with corresponding structures of significance 19 and micro-roughness 15. The lower section shows the same eroded surface after smoothing according to the present method. It is

clearly visible that the micro-structures have been completely removed and but that the structures of significance 19 are still present. Changing the treatment parameters during treatment results in varyingly strongly smoothed structures, and in this way different gray hues can be realized, for example for creating inscriptions on a surface.

## List of References

| | |
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| 1 | surface |
| 2 | workpiece |
| 3 | laser beam |
| 4 | section of the surface, resp. treatment field |
| 5 | track width |
| 6 | path |
| 7 | beam diameter |
| 7a | beam cross section |
| 8 | track off set |
| 9 | path length |
| 10 | first remelting depth |
| 11 | height of the macro-roughness |
| 12 | width of, resp. distance, the macro-roughness |
| 13 | edge |
| 14 | second remelting depth |
| 15 | micro-roughness |
| 16 | untreated area |
| 17 | treated area after the first treatment step |
| 18 | treated area after the second treatment step |
| 19 | structures of significance |
| 20 | removed material |